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# Influence of bondcoat creep and roughness on damage and lifetime of $\text{ZrO}_2$ TBCs for gas turbines under thermocyclic loads

**M Schweda, T Beck, L Singheiser**

Forschungszentrum Jülich GmbH, IEF-2, 52425 Jülich

t.beck@fz-juelich.de

**Abstract.** As a simplified model system for thermal barrier coatings (TBCs) in gas turbines,  $\text{Y}_2\text{O}_3$  partially stabilized  $\text{ZrO}_2$  TBCs were applied on FeCrAlY substrates. The creep strength of the substrate was varied by using an oxide-dispersion-strengthened (ODS) alloy and a non-ODS alloy with similar chemical composition. Defined interface profiles were produced before coating. Creep properties of the oxide layer between substrate and TBC were varied by either coating the test pieces with nanocrystalline PVD-alumina or with coarser grained naturally grown  $\text{Al}_2\text{O}_3$  before plasma spraying the TBC. During thermal cycling ( $T_{\text{max}}=1050^\circ\text{C}$ ,  $T_{\text{min}}=60^\circ\text{C}$ , dwell of 2 hours at  $T_{\text{max}}$ ) periodic 2-d interfaces resulted in very low lifetime independent from substrate strength and interface oxide type. With stochastic 3-d interfaces lifetimes up to 900 cycles were reached, especially for the substrate with low creep strength combined with a coarse grained alumina interlayer.

## 1. Introduction

To protect blades and vanes in the first stages of gas turbines from overheating and hot corrosion,  $\text{Y}_2\text{O}_3$  partially stabilized  $\text{ZrO}_2$  (PYSZ) thermal barrier coatings (TBC) are used with NiCoCrAlY bondcoats (BC) forming a dense, thermally grown oxide (TGO) layer between TBC and BC. Thermal mismatch stresses between these components and TGO growth stresses promote cracks near the TBC/BC interface [1]. Creep of BC and TGO as well as the roughness of the BC/TBC-interface significantly affect the stress state in the TBC system and therefore determine its lifetime [2]. In the present study a simplified TBC system consisting of a plasma-sprayed PYSZ TBC applied on solid FeCrAlY substrates simulating the BC was investigated under thermocyclic loadings. The Ni base substrate was excluded to avoid additional thermal mismatch and interdiffusion. A conventional Fe-CrAlY substrate and an ODS alloy with similar chemical composition were used to investigate the influence of BC creep strength. The influence of interface roughness was analyzed by applying periodic 2-dimensional roughness profiles by high speed turning and stochastic 3-dimensional roughnesses

by sand blasting. The influence of creep strength of the TGO layer between BC and TBC was investigated by applying either a nanocrystalline  $\text{Al}_2\text{O}_3$  layer by sputtering or a naturally grown  $\text{Al}_2\text{O}_3$  layer with grain sizes in the range of  $1\mu\text{m}$  before plasma spraying of the TBC. All samples were subjected to thermocyclic fatigue with in-situ and ex-situ observation of delamination cracking.

## 2. Experimental Details

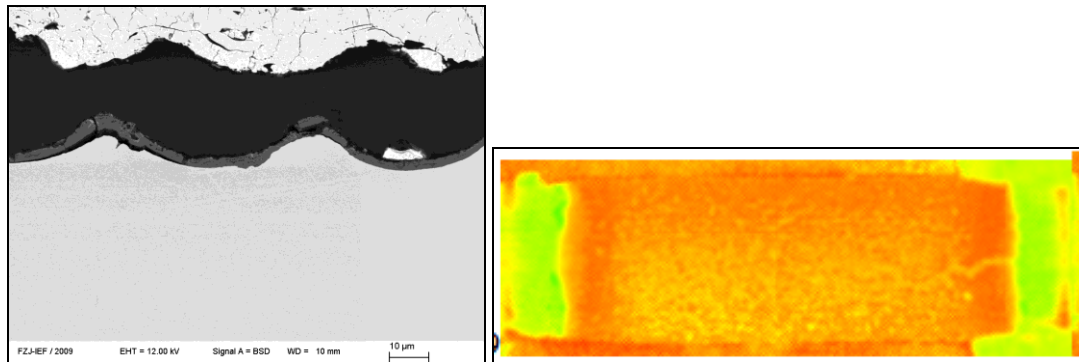
The FeCrAlY substrates were Fecralloy Eisen-Chrom<sup>TM</sup> and MA956<sup>TM</sup>. The main alloying elements are 22% (20%) Cr, 4.8% (4.5%) Al, and 0.3% (0.5%) Y (weight.-%, numbers in brackets: MA956). The solid cylindrical specimens had a length of 25 mm, and a diameter of 8 mm. The peak-to-peak roughness of the interfaces was  $10\mu\text{m}$ ,  $15\mu\text{m}$  and  $20\mu\text{m}$  with wavelengths between 40 and  $45\mu\text{m}$ . The fine grained  $\text{Al}_2\text{O}_3$  layer applied by sputtering had an initial grain size of 100 up to 200 nm which increased during thermal cycling to  $\approx 500\text{ nm}$ . The alumina interlayer applied by oxidation had initial grain sizes between 0.5 and  $1.0\mu\text{m}$  which did not change significantly during thermal cycling. The  $\text{ZrO}_2 / 7\% \text{ Y}_2\text{O}_3$  TBC with  $200\mu\text{m}$  thickness was applied at Universität Braunschweig, IfW, along 20 mm in the middle of the samples with smoothly decreasing thickness towards the ends of the test pieces in order to minimize edge effects. Thermal cycles were applied in air with  $T_{\text{max}}=1050^\circ\text{C}$ ,  $T_{\text{min}}=60^\circ\text{C}$ , and a dwell of 2 hours at  $T_{\text{max}}$  using a resistance furnace with a pneumatic actuator periodically placing the sample inside and outside the furnace. The samples were examined by infrared impulse thermography to quantify delaminations under the TBC with a resolution of 0.2 mm. After failure by segmentation cracking of the TBC the samples were cross sectioned and examined by SEM.

## 3. Results and Discussion

### 3.1. Periodic 2-dimensional interface

Lifetimes were extremely short in the case of periodic 2-d interfaces. The samples with the highest peak-to-peak roughness, naturally grown  $\text{Al}_2\text{O}_3$  interlayer and Fecralloy substrate (low creep strength) reached up to 40 cycles until macroscopic segmentation was observed. All other specimens failed at cycle numbers up to 10. In all cases delamination occurred mainly along the  $\text{Al}_2\text{O}_3$ /TBC interface with few cracks in the  $\text{Al}_2\text{O}_3$  and at the  $\text{Al}_2\text{O}_3$ /substrate interface. Infrared thermography showed large longitudinal and tangential delaminations (Figure 1). These results allow the following conclusions:

- Tangential crack growth is very fast due to the fact that no roughness exists in this direction.
- The fast longitudinal crack growth indicates that the periodicity of the profile increases the crack growth rate compared to stochastic 3-dimensional profiles (see section 3.2).
- Increasing interface roughness rises lifetime because mechanical interlocking is essential for sufficient attachment of plasma sprayed TBCs to the substrate.

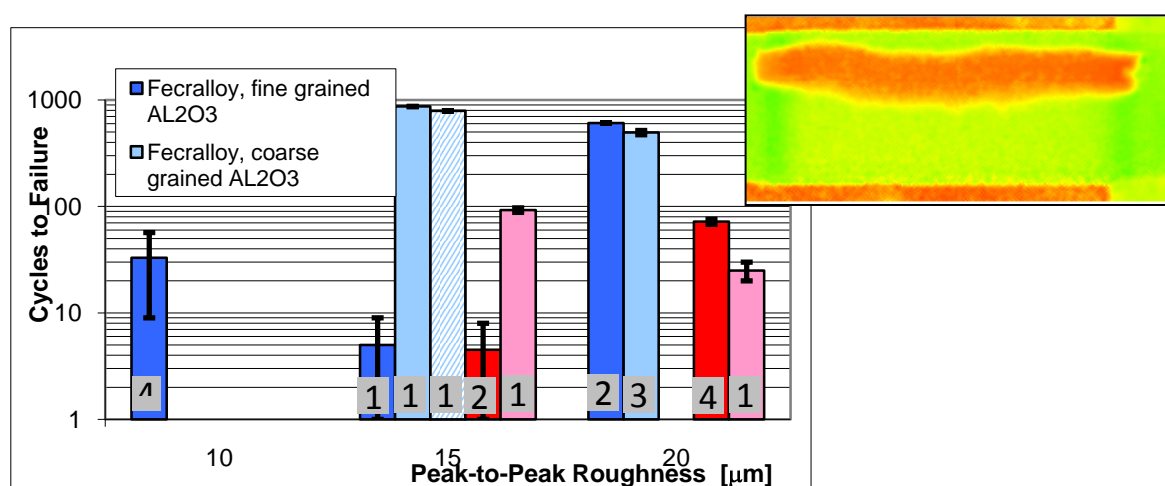


**Figure 1.** Delamination crack path (left) and thermography image (right, red areas indicate delamination) of a specimen with Fecralloy substrate, periodic 2-dimensional interface and naturally grown alumina

### *1.2. Stochastic, 3-dimensional interface*

Figure 2 gives an overview of the lifetimes measured in the case of stochastic, 3-dimensional interfaces. The numbers inside the bars indicate the position of the delamination cracks determined by SEM at cross sections after failure. In addition to the samples with coarse grained or with nanocrystalline alumina layers applied before TBC application, in the intermediate roughness class two samples were tested without an initial  $\text{Al}_2\text{O}_3$  layer. In this case, a naturally grown TGO with relatively high grain size (around  $1\mu\text{m}$ ) is formed as in real-life TBC systems. The exemplarily chosen thermography image shows that crack propagation occurs mainly in longitudinal direction. It should be noted that a quantitative analysis of delamination crack growth using infrared thermography indicated an incubation phase with crack lengths below 0.2 mm followed by nearly linear or progressive crack growth as reported in [3]. From these results the following conclusions are drawn:

- Distinctly higher lifetimes are found in the case of Fecralloy-substrate (low creep strength) compared with MA956 (high creep strength).
- For high roughness, the fine grained  $\text{Al}_2\text{O}_3$  interlayer leads to similar or higher lifetimes than the coarse grained  $\text{Al}_2\text{O}_3$ .
- The lifetime in the reference case with no initial alumina interlayer is nearly equal to the result for a coarse grained interlayer. This indicates that the attachment of the TBC is not adversely affected by preoxidation of the substrate before plasma spraying.
- In the case of smaller roughness, the fine grained  $\text{Al}_2\text{O}_3$  results in distinctly lower life than the coarse grained variations (naturally grown and applied by pre-oxidation).
- Increasing roughness and increasing substrate creep strength tends to shift the crack to the  $\text{Al}_2\text{O}_3$  and the  $\text{Al}_2\text{O}_3$ /substrate interface.



**Figure 2.** Lifetimes of the model TBC systems with stochastic 3-d interface. The numbers indicate the delamination crack path: (1) – TBC and TBC/Al<sub>2</sub>O<sub>3</sub> interface; (2) – TBC/Al<sub>2</sub>O<sub>3</sub> interface; (3) – TBC, TBC/Al<sub>2</sub>O<sub>3</sub> interface and Al<sub>2</sub>O<sub>3</sub>; (4) – TBC/Al<sub>2</sub>O<sub>3</sub> interface, Al<sub>2</sub>O<sub>3</sub> and Al<sub>2</sub>O<sub>3</sub>/substrate interface. The inlay picture is a typical thermography image at end of life

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